ENERGY FRONTIER WORKSHOP GOALS

Energy Frontier Community Workshop, July 20-22, 2020

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Workshop Goals

- Develop Physics Focus questions and benchmarks

- Start thinking about technical baselines
  - accelerators
  - instrumentation
  - computation

Workshop Theme: Open Questions and New Ideas

- A plethora of studies for physics sensitivities for various future colliders exist in various CDRs and TDRs etc. These studies serve as a baseline for us. We want to focus on *"open questions"* which are identified by these studies.
- *New ideas* are always welcome! We need to make the case stronger.
- *Defining baselines* is a guidance for where to start, and connect with the studies which already exist.
  - Define Accelerator baselines to consider
  - Define Instrumentation baselines
  - Understand Computational needs
- However, if the sensitivities for physics scenarios can improve considerably with some change in the machine parameter, or the detector design, we should consider them!

- **Snowmass is our time to innovate and set new directions without barriers and constraints set by our collaborations.**

Developing Focus Questions

- **We have started to formulate sharp questions which bring focus to issues pertaining to the future of the Energy Frontier, and helps define the message and activities of the Energy Frontier**

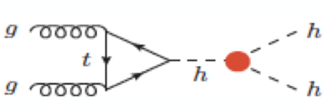
- The “Big Focus Questions or Ideas”:
  - Should be “Physics Driven”
  - Should highlight “scientific merit” of various collider options
  - Should highlight connections with other Frontiers
  - Should re-evaluate existing ideas and emphasize how existing work can lead to new ideas (for example HL-LHC results may shape future colliders…)

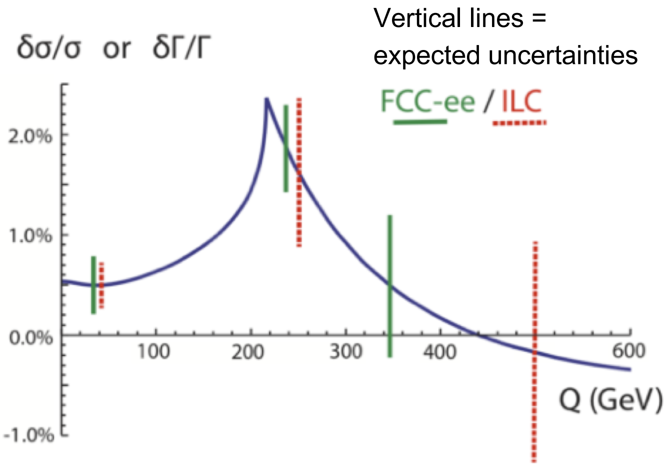
- We have to develop these questions within each Topical Group
  - of course with overlaps!
- These will serve as a starting point for the Final Report (not due till later in 2021) but will also serve as a checkpoint of activities for the October Community Planning workshop [Oct 5 week].

EF01-04: Higgs, Top, EW

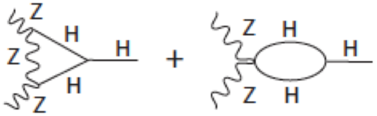
- What is the scale of New Physics that can be probed with precision measurements?
  - How precise do SM Higgs measurements need to be in order to probe BSM physics scenarios?
  - What theory calculations are needed to enable the theory precision to match the projected experimental precision of future measurements?
- Does the Higgs boson result from the scalar potential of the Standard Model? How can measurements of double Higgs boson production be improved to better probe the potential?
- What colliders/experiments could allow a measurement of OR be upgradeable to allow the measurement of:
  - All Yukawa couplings with 100% precision?
  - $\lambda 3$ at better than 0.1% precision?
  - $\lambda 4$ at better than 1% precision?
- How do current collider scenarios cover existing benchmark scenarios?
- What additional benchmarks scenarios are needed?

Higgs self coupling

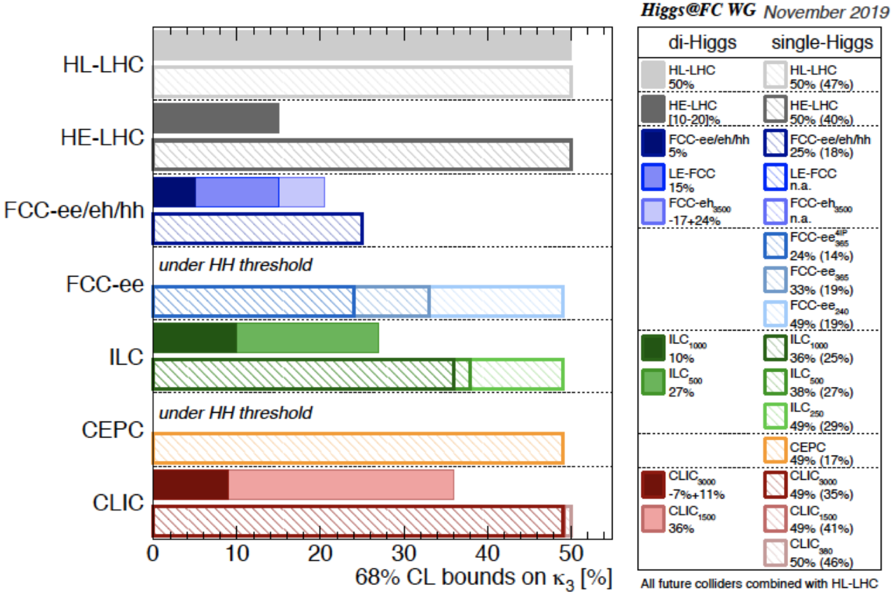




Single H extraction method: relative enhancement of the $e^+e^- \to ZH$ cross-section and the $h \to W^+W^-$ partial width, in %, for k_λ=1, due small but momentum dependent radiative corrections.



Precision with which h^3 can be measured

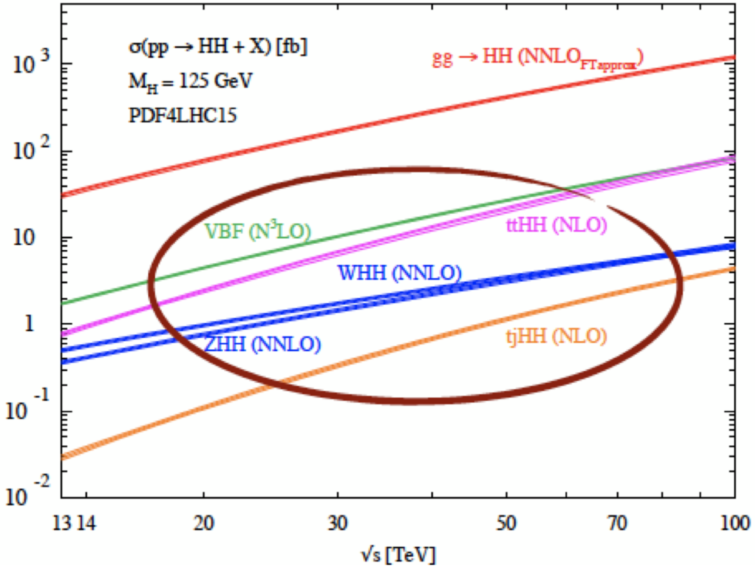


50% sensitivity: establish that $h^3 \neq 0$ at 95%CL
20% sensitivity: 5σ discovery of the SM h^3 coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

https://arxiv.org/pdf/arXiv:1910.00012.pdf

What about other HH mechanisms?

extend studies during Snowmass 2021



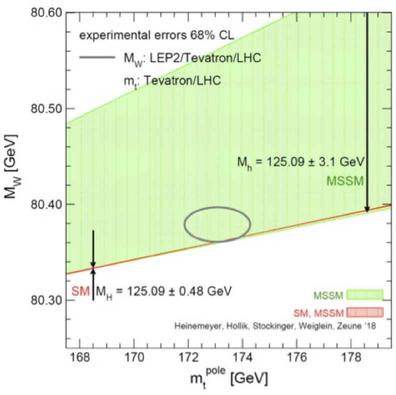
EF01-04: Higgs, Top, EW

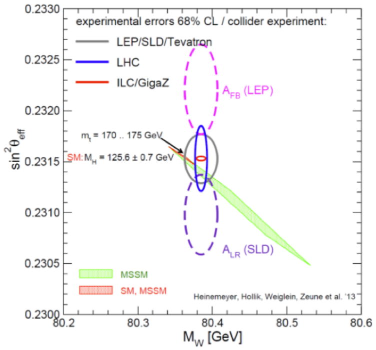
- How can measurements in the Higgs sector be combined with measurements in other sectors to improve our understanding of high scale physics?
  - Higgs+EW+top precision fits
- How can the top quark help elucidate the Higgs sector and inform about possible physics beyond the SM?
  - What is the ultimate precision for the measurement of a well-defined top-quark mass?
  - How much does it improve the reach of a global EW precision fit?
- What are the optimal top-quark observables for constraining EW top-quark couplings in EFT fits? What can we learn from these constraints about BSM physics?
- What can be learned from measurements of top-quark properties other than m_{top} and couplings, such as spin correlations, asymmetries, polarization in new kinematic regimes, and what is the achievable/required precision?
- What can be learned from precision measurements of heavy-quark production (cc,bb,tt) at lepton colliders? Are systematic uncertainties from theory under control (especially higher-order EW corrections?)

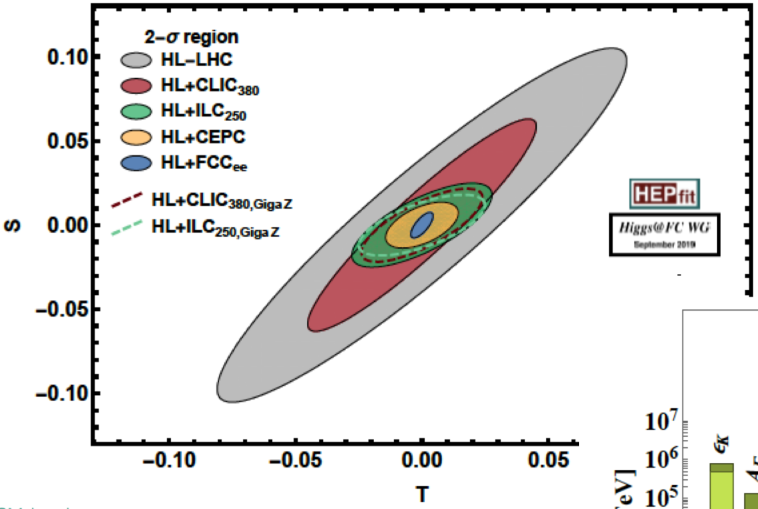
Precision observables

- Probing the energy scale for new physics:

[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '





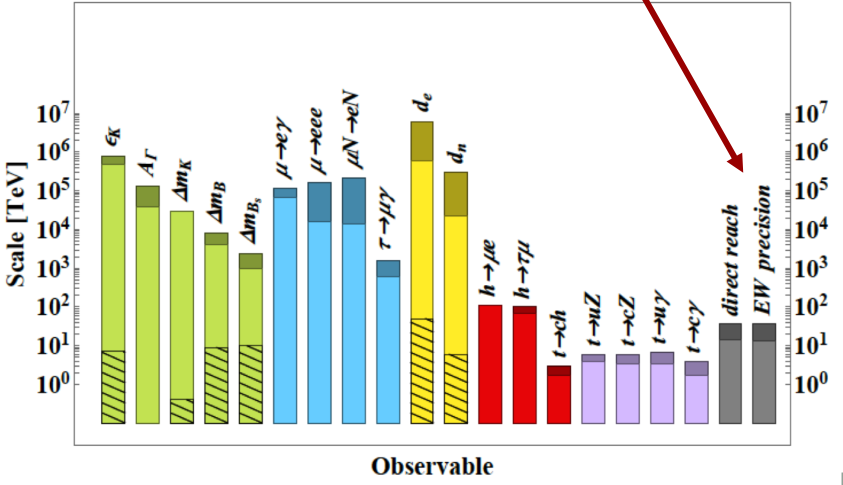


MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

How can we do better?



ESG Briefing book Fig 5.1

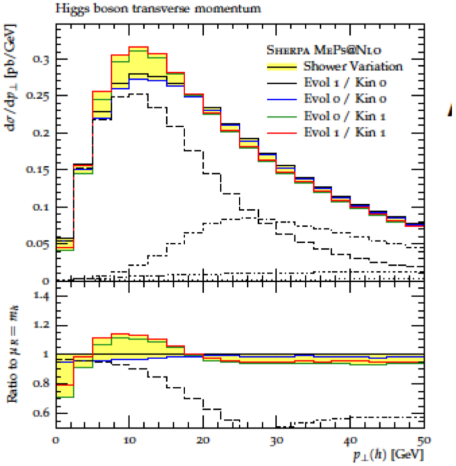
EF05-07: QCD and Strong Interactions

- Precision QCD
  - What is the ultimate precision for α_s and how do we achieve it? From the LHC, future pp, future e+e-, DIS (ep and eA), particle decays (tau, hadrons), and lattice QCD.
  - What theoretical developments are needed to support precision measurements of Higgs and top quark production and properties (including electroweak corrections, non-perturbative threshold effects)?
  - Evaluation and interplay of uncertainties from theory and from experiment.
    - Theory correlations in experimental measurements, how?
    - Theoretical scales used in PDF extraction
    - Non-perturbative effects → cross-cutting effort between lattice QCD and MC community
  - Parton shower development.
    - EW emission, color flow, multi-parton interactions, scale choices.
    - Inclusion of higher-order calculations in MC event generators (NNLO QCD, NLO QCD+EW)
  - Jet substructure observables.

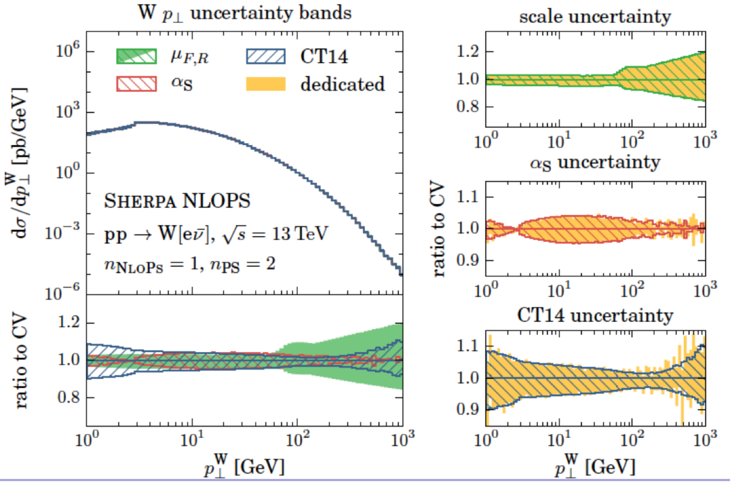
Uncertainties in Monte Carlo Event Generation

- Factorize into event stages according to characteristic scales, use relevant approximation in each regime: Hard scattering, Parton evolution, Multiple interactions, Hadronization, Hadron decays, QED corrections
- Broadly categorized into Parametric, Perturbative, Algorithmic and Modelling uncertainties

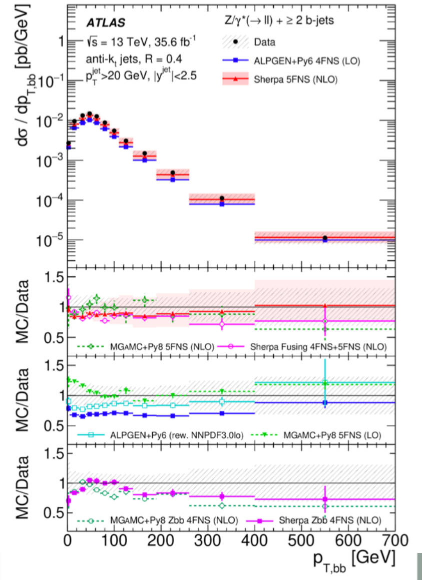
Parton showers
Algorithmic: diff choices of evolution and recoil schemes



parametric: uncertainty in model parameters, non perturbative inputs



Heavy Flavor



Parton Distributions: Challenges for Snowmass 2021

PDF-related topics in Snowmass'13 [arXiv:1310.5189] and 21' studies

Topic	Status, 2013	Status and plans, 2020
Benchmarking of PDFs for the LHC	Before PDF4LHC'2015 recommendation	In progress toward PDF4LHC'2X recommendation
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	Needs an update using LuXQED and other photon PDFs; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Needs an update for PDFs with small-x and threshold resummations
Parton luminosities at 14, 33, 100 TeV	CT10, MSTW2008, NNPDF2.3 Update at 100 in CERN YR (1607.01831)	Need an update based on the latest PDFs
LHC processes to measure PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production	updates on these processes + $Q\bar{Q}$, dijet, $\gamma/W/Z$ +jet, low-Q DY, …
Future experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3 DIS: EIC, LHeC, …

NEW TASKS in THE HL-LHC ERA:

Obtain complete NNLO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast NNLO interfaces	Estimate NNLO theory uncertainties	Develop an agreement on comparing and combining PDF fits

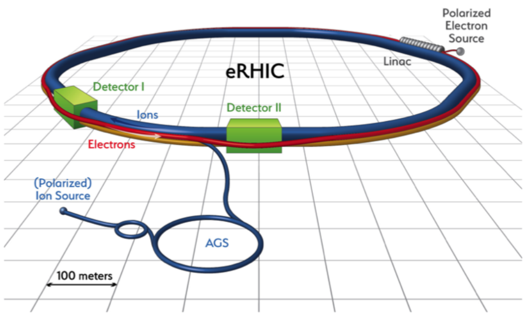
EF05-07: QCD and Strong Interactions

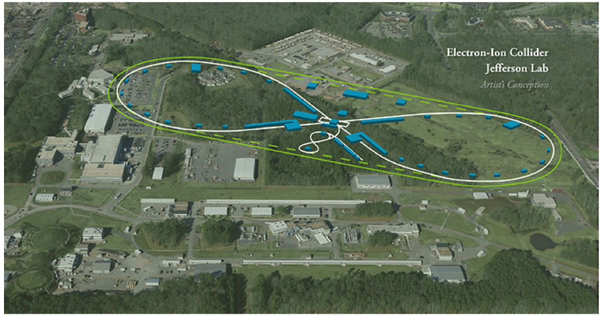
- Hadronic structure
  - What is the future of PDF determinations?
    - What is the potential of new deep inelastic scattering facilities (EIC, LHeC & FCC-eh) for probing the hadronic and nuclear structure in the regions relevant for HEP experiments?
    - How can the experience of the HEP community be transferred to enhance the potential of the EIC and LHeC studies?
    - What is the best approach to reduce systematic uncertainties in LHC measurements to achieve the accuracy of PDFs envisioned by electroweak precision studies at the future hadron colliders?
    - What is a feasible strategy for obtaining accurate PDFs for N3LO QCD computations? Which theoretical advances and computational tools will be necessary?
  - How does the knowledge of hadron structure affect measurements of α_s in various processes?
  - How can LHC, LHeC, and FCC improve our knowledge of the 3-dimensional structure of nucleons and nuclei?
  - How do excited hadronic states with two or more heavy quarks form and decay?
  - What are the BSM connections for hadron spectroscopy at future facilities?

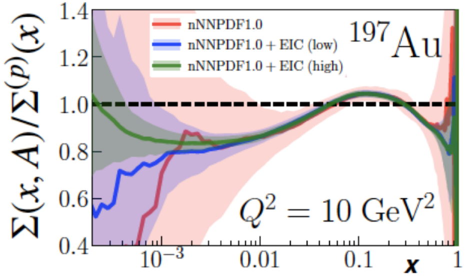
EF05-07: QCD and Strong Interactions

- Forward Physics
  - What are the prospects of running forward proton detectors at the HL-LHC and at future hadron colliders?
  - Which detectors (including acceptance/resolution) will be needed at the LHC and the EIC to perform the best possible measurements of energy, particle production in the very forward region?
  - What will be their sensitivity to anomalous couplings between photon, W, Z bosons, top quarks.
  - How to observe saturation effects or high-gluon density regimes at the LHC and the EIC?
- Heavy Ions
  - What can we learn from the jet and jet substructure measurements about the nature of the quark-gluon plasma? How do we apply the techniques to the studies of jets and the possible jet energy loss in EIC?
  - What is the best use of heavy-ion beams for the search of new physics?
  - What are the heavy quark and quarkonia production mechanisms in ee, eA, pp, pA and AA collisions? What is the relevance of co-moving matter effects and recombination for the classical observables e.g charm and beauty jet?
  - How do we use heavy-ion beam to improve the understanding of inclusive hadron and charm production? What is the connection to the new physics search at forward region and the studies of cosmic rays?

Nuclear/nucleon structure at the Electron-Ion Collider



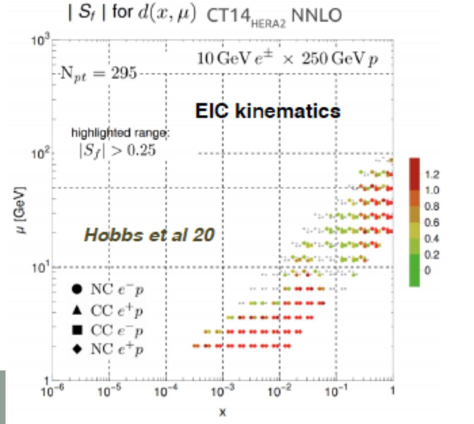




Abdul-Khalek et al 19

Pinning down nuclear PDFs at small-x: onset of gluon-dominated matter?

- Synergies between EIC, proton PDF fits, and LHC pheno deserve attention
  - Probably, EIC is likely the only lepton nucleon collider operating in the near future!
  - Assess impact on proton PDFs of simulated EIC pseudo-data
- What can the EIC do for proton PDFs?
  - Replace the old fixed target DIS data
  - Improved, cleaner coverage of large-x region
  - Robust large-x sea quarks from deuteron projectiles
  - New probes of the gluon from jets ….
  - *lots of unexplored potential!*



EF08-10: BSM

- Naturalness has many faces. How can future colliders address these puzzles of nature to an extent that either new physics will appear or a new paradigm of thinking about the naturalness problem can emerge?
- How does naturalness guide which measurements are most relevant for a particular model, and when that model becomes less attractive?
  - If we exclude parameter space XYZ how will the field be advanced?
  - How will the relative fine-tuning change before and after project XYZ?
- What is the additional source of CP violation needed to explain the matter-antimatter asymmetry observed in our universe? How can we address the origin of this matter antimatter asymmetry of our universe via future colliders?
- Can the underlying explanation of the flavor structure of the SM be probed with existing or technologically envisionable EF machines?
- What are the best techniques to search for lepton universality violation? What do we learn from high energy/pT searches?
- What is the fundamental composition of Dark Matter, what are the best ways probe the composition of DM and whether it interacts weakly?

EF08-10: BSM

- To what extent can future experiments and colliders probe new interactions or particles around or above the EW scale?
- Long-lived and feebly-interacting particles represent an alternative paradigm with respect to traditional BSM searches. To what extent can future detectors and accelerators probe such particles?
- Which models to consider? What are the appropriate benchmarks?
  - What mass higgsino will still be allowed if we build XYZ
  - What scale SUSY (RPC/RPV) or RS/Composite Higgs can be probed
- How to compare broad model spaces in a concise and effective way?
  - Simplified models are often used but may not be representative of the full space
  - Compare inclusivity of leptons colliders vs reach of hadron colliders
  - Compare direct searches vs indirect constraints from precision measurements
- How do we conduct searches in a more model-independent way?
- How do we compare the results of different experiments in a more model-independent way to ensure complementarity and avoid gaps in coverage?

New Resonances

Future colliders extend significantly the reach for heavy resonances

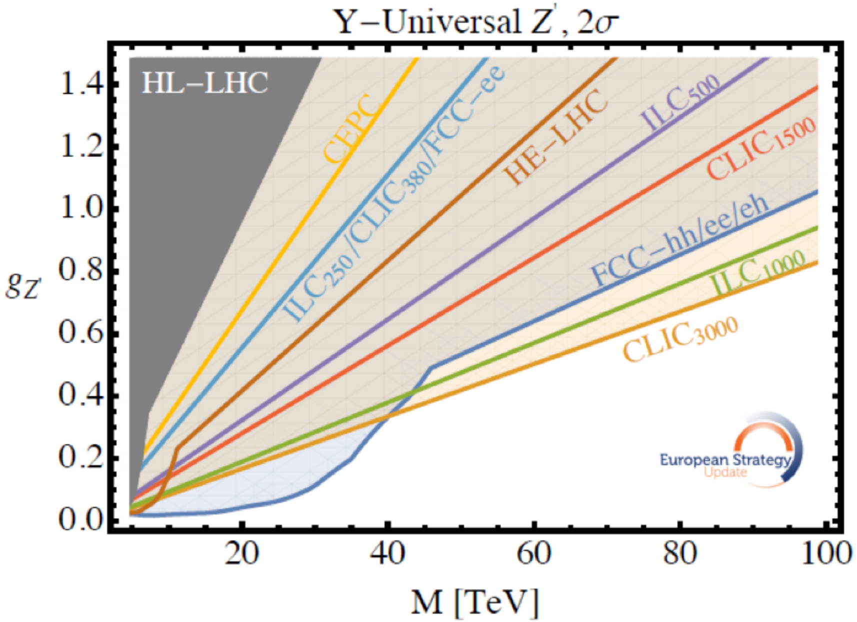
- Includes characterization of the resonances and the ability to differentiate between models
- Hadron and lepton machines are complementary

Rich future programs

- Resonance vs Precision
- Rich phenomenology
- Many different channels

Open questions to address including how to:

- fully exploit boosted topologies (e.g. VLQ topologies not much studied at 100 TeV)
- develop state-of-the-art W/top/Higgs taggers
- Study impact of detector choices: e.g. calorimeter granularity, tracking
- Improve high pT b-jet tagging (also boosted b-jet tagging)
- Better optimize/study tau final states
- Better estimation of systematic effects, broader set o models w/ diff couplings to generations, lepton/quark…

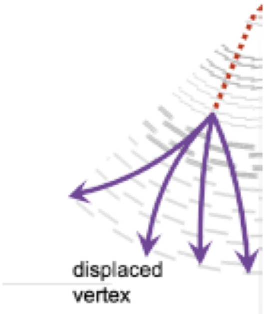


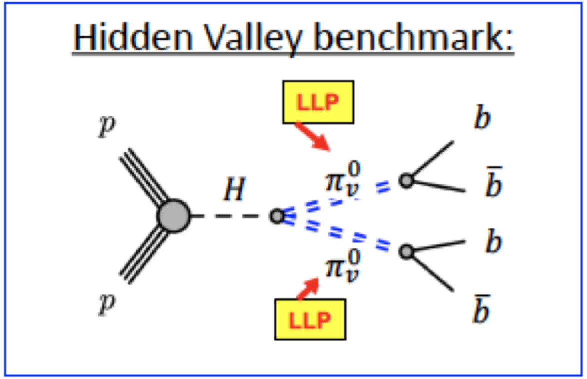
Long Lived Particles

Explore LLPs at both future hadron colliders, and lepton colliders (CLIC, FCC-ee)

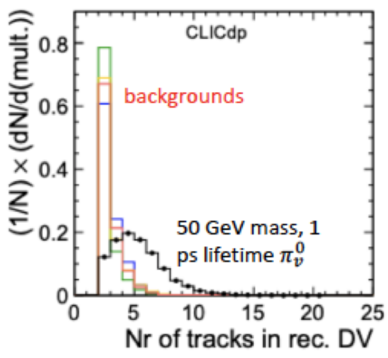
- Lepton colliders have a cleaner collision environment than hadron colliders
  - CLIC–Possibility of readout without a trigger
  - First layers of pixels could be closer to the interaction point
- Search for Higgs bosons that decay to long-lived particles that decay to b quarks with a signature of displaced, multi-track vertices
  - Results with full CLIC_ILD detector simulation
  - Use BDT to separate signal from background

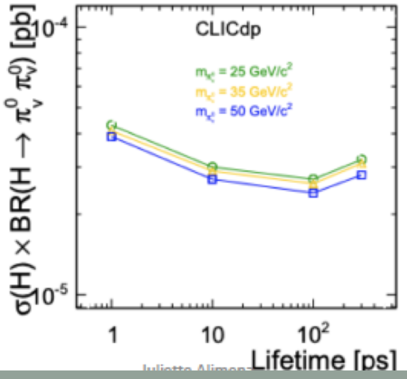
Good sensitivity to long-lived Higgs bosons in clean environment at CLIC





An input variable to the BDT:





Accelerators for Energy Frontier Studies

- Energy Frontier science goals currently envision two types of future colliders (in arbitrary order)
  - Higgs (and other known elementary particles) factory
  - Next high energy frontier machine
- Discoveries at the Energy Frontier are intricately linked to the progress in accelerators.
- To do physics studies of options, and to make a physics case, machine parameters, and estimates of luminosity and backgrounds are needed for the proposed options.

- Two Joint AF-EF Meeting on Future Colliders were hosted by the AF.
  - These were very helpful in providing a table with parameters, technical readiness/feasibility, cost, timeframe for start of construction, for the various collider options

Joint AF-EF Meeting on Future Colliders

- Day 1: June 24, 2020 – Projects with TDRs or CDRs
- Day 2: July 1, 2020 – off-mainstream yet

Classify options by technical maturity & timeframe

Day 1: https://indico.fnal.gov/event/43871

9:00 AM	→ 9:10 AM	**Introduction: goals, format, etc**
9:10 AM	→ 9:25 AM	**FCCee** **Speaker**: Katsunobu Oide (KEK)
9:25 AM	→ 9:40 AM	**CepC** **Speaker**: Yu Chenghui
9:40 AM	→ 9:55 AM	**ILC** **Speaker**: Shinichiro MICHIZONO (KEK)
9:55 AM	→ 10:10 AM	**CLIC** **Speaker**: Steinar Stapnes (FNAL)
10:10 AM	→ 10:25 AM	**EIC** **Speaker**: Christoph Montag (BNL)
10:25 AM	→ 10:40 AM	**LHeC** **Speaker**: Oliver Bruning (CERN)
10:40 AM	→ 10:55 AM	**HE-LHC** **Speaker**: Frank Zimmermann (CERN)
10:55 AM	→ 11:10 AM	**SppC** **Speaker**: Jingyu Tang (Institute of High Energy Physics)
11:10 AM	→ 11:25 AM	**FCChh** **Speaker**: Michael Benedikt

Day 2: https://indico.fnal.gov/event/43872/

9:00 AM	→ 9:10 AM	**Introduction: gioals, format, etc**
9:10 AM	→ 9:30 AM	**Cold NC-Linear Collider** **Speaker**: Emilio Nanni (SLAC National Accelerator Laboratory)
9:30 AM	→ 9:50 AM	**ERL based FCCee** **Speaker**: Thomas Roser (BNL)
9:50 AM	→ 10:10 AM	**Gamma-Gamma Higgs factories** **Speaker**: Frank Zimmermann (CERN)
10:10 AM	→ 10:30 AM	**Plasma-Laser WFA 1 TeV +** **Speaker**: Carl Schroeder (Lawrence Berkeley National Laboratory)
10:30 AM	→ 10:50 AM	**Plasma-Beam WFA 1 TeV +** **Speaker**: Spencer Gessner
10:50 AM	→ 11:10 AM	**Structure-beam WFA 1 Tev +** **Speaker**: John Power (Argonne National Lab)
11:10 AM	→ 11:30 AM	**Muon Coliders: Higgs Factory and 3-14 TeV** **Speaker**: Daniel Schulte (CERN)
11:30 AM	→ 12:10 PM	**Discussion/ Q&A**

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We requested Machine Parameter "Standard Tables"

Facility "Standard Table"

Facility / Your name*	Particle species	* Contact email for Qs
Beam Energy	GeV	
Peak Luminosity (10^34)	cm-2 s-1	
Int. Luminosity	ab-1/yr	
Beam dE/E at IP		
Transv. Beam sizes at IP x/y	um	
Rms bunch length / beta*	cm	
Crossing angle	urad	
Rep./Rev. frequency	Hz	
Bunch spacing	ns	
# of IPs		
# of bunches		
Length/Circumference	km	
Facility site power	MW	
Cost range	$B US	(day 2 speakers – feel free to skip)
Timescale till operations		

Accelerators for Energy Frontier Studies

- Outcome of the Joint AF-EF Meeting on Future Colliders.
  - All “standard tables” are compiled and and posted on Day 2 Indico https://indico.fnal.gov/event/43872/ https://indico.fnal.gov/event/43872/attachments/129328/159581/SummaryTables_AF-EF_d1d2.pdf
  - In addition to “readiness” other major features for classifications considered are:
    - for accelerator builders: performance(luminosity reach), cost and power efficiency(total power);
    - and for particle physicists – physics reach(energy) and detectors(backgrounds)
- The tables will form the baseline for the studies pursued by the Energy Frontier
- Inputs from AF topical groups for the EF physics studies is critical.
  - AF3: Accelerators for EW/Higgs
  - AF4: Multi-TeV Colliders
  - AF6: Advanced Accelerator Concepts
- One of the challenges for EF is to evaluate the trade-offs and narrow the range of collider options to explore
- It will be an iterative process between AF and EF groups to identify most valuable options

Some partial "Snapshots"

- CepC

CepC	e+e-	Yu Chenghui
Beam Energy	GeV	120
Peak Luminosity (10^34)/IP	cm-2 s-1	3.0
Int. Luminosity	ab-1/year	1.4
# of IPs		2
Cost range	$B US	5.0
Timescale till operations		2030

- FCC-ee

	e^+e^-	katsunobu.oide@cern.ch			
Beam Energy, range	GeV	45.6, ±2	80, ±2	120, -10+5	182.5, -12+2
Peak Luminosity (10^34)	cm-2 s-1	460 / 2IP	56 / 2IP	17 / 2IP	3.1 / 2IP
Int. Luminosity	ab-1/yr	48 / 2IP	6 / 2IP	1.7 / 2IP	0.34 / 2IP
# of IPs		2			
Cost range	$B US	10.5 (BCHF)			+1.1 (BCHF)
Timescale till operations	yr	19	+4	+2	+4

- CLIC

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Total luminosity	$\mathscr{L}$	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\mathrm{int}}$	fb^{-1}	180	444	708

- ILC

ILC	electron/positron	ILC250
Beam Energy	GeV	125 (e-) and 125 (e+)
Peak Luminosity (10^34)	cm-2 s-1	1.35
Int. Luminosity	ab-1/yr	0.24*
# of IPs		1
Cost (value) range	$B US	~5 (tunnel and accelerator)
Timescale till operations	years	(~1) + 4(prep.) + 9(construction)

- ILC energy & luminosity upgrade

			Z-Pole [4]		Higgs [2,5]			500GeV [1*]		TeV [1*]
			Baseline	Lum. Up	Baseline	Lum. Up	L Up.10Hz	Baseline	Lum. Up	case B
Center-of-Mass Energy	E_{CM}	GeV	91.2	91.2	250	250	250	500	500	1000
Beam Energy	E_{beam}	GeV	45.6	45.6	125	125	125	250	250	500
Luminosity	L	$10^{34}/\mathrm{cm}^2/\mathrm{s}$	0.205	0.410	1.35	2.70	5.40	1.79	3.60	5.11
Luminosity enhancement factor	H_D		2.16	2.16	2.55	2.55	2.55	2.38	2.39	1.93
Luminosity at top 1%	$L_{0.01}/L$	%	99.0	99.0	74	74	74	58	58	45

Some partial “Snapshots”

- FCC-hh

FCC-hh	p-p (p-A, A-A)	michael.benedikt@cern.ch
Beam Energy, range	TeV	50
Peak Luminosity (10^34)	cm-2 s-1	30
Int. Luminosity	ab-1/yr	1.5-2 / 2IP
# of IPs		4 (2 with high-luminosity)
Cost range	$B US	17 following FCC-ee in integrated program 24 standalone
Timescale till operations	yr	35-45

- SppC

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	100	100
C.M. energy	TeV	70.6	75	125-150
Number of IPs		2	2	2
Nominal luminosity per IP	$cm^{-2}s^{-1}$	1.2e35	1.0e35	-
Int. Luminosity	ab-1/yr			-
Cost range				
Timescale till operation				

Some partial "Snapshots"

- HE-LHC

HE-LHC	p-p (p-A, A-A)	* frank.zimmermann@cern.ch
Beam Energy	GeV	13500 (p-p)
Peak Luminosity (10^{34})	$cm^{-2}s^{-1}$	16 (p-p)
Int. Luminosity	ab^{-1}/yr	≥0.5
# of IPs		2
Cost range	$B US	7-8
Timescale till operation		> 2050

- Muon Collider

Muon Collider Parameters From the MAP collaboration: Proton source

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000

Paramete r	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20

Some partial "Snapshots"

- LHeC

EIC/Christoph Montag	e - p	Montag@bnl.gov
Beam Energy	GeV	e: 5, p: 41
Peak Luminosity (10^34)	cm-2 s-1	0.044
Int. Luminosity	ab-1/yr	4.4
# of IPs		1 (up to 2)
Cost range	$B US	$1.6B - $2.6B
Timescale till operations		~2030

- EIC

EIC/Christoph Montag	e - p	Montag@bnl.gov
Beam Energy	GeV	e: 5, p: 41
Peak Luminosity (10^34)	cm-2 s-1	0.044
Int. Luminosity	ab-1/yr	4.4
# of IPs		1 (up to 2)
Cost range	$B US	$1.6B - $2.6B
Timescale till operations		~2030

Some “Open Questions” from AF for EF to consider

- Shall we add other CoM options for very high energy pp collider? Currently studies use 100 TeV, shall we add an intermediate √s e.g. 70 TeV and lower com point?
  - 100 TeV with 16T magnets would have an unacceptably long timeline and cost too much.
  - 75 TeV with 12T magnets is feasible but still very expensive.
  - It was suggested to start with 6-7T Nb-Ti magnets. Is 40 TeV CoM of any interest?

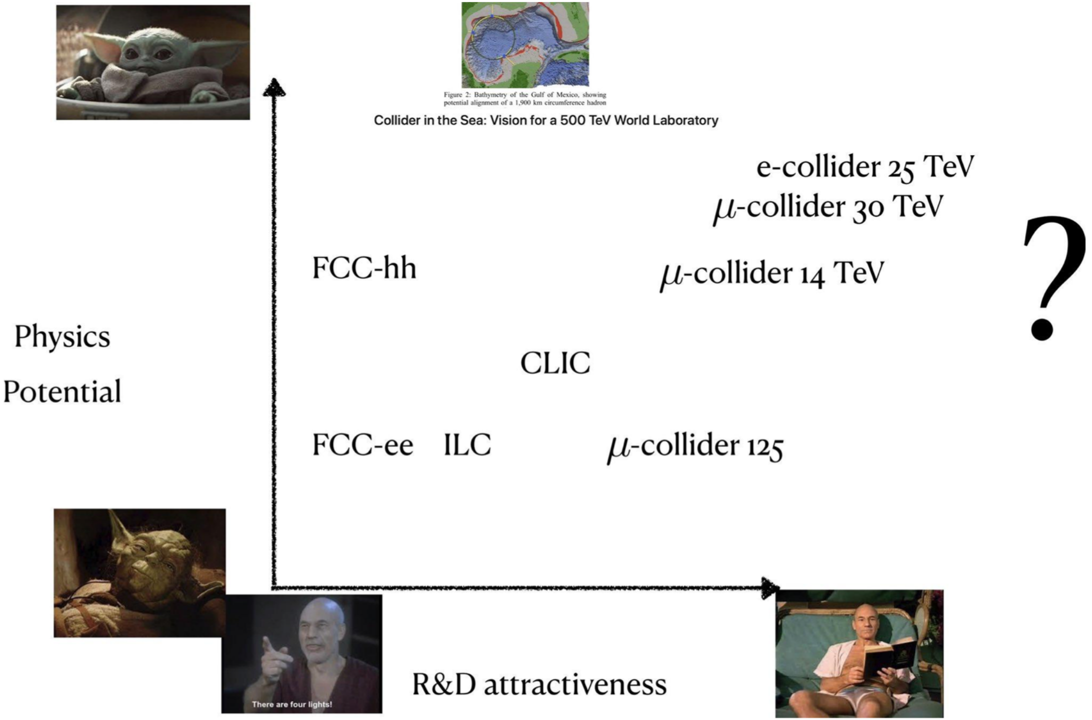
- Muon Collider:
  - The √s options presented were multi-TeV (3, 6, 10, 14 TeV)
  - Shall we also pursue muon-collider as a Higgs Factory? low lumi very narrow dE/E?
  - is there interest in √s 30 and 100 TeV “dream” machines – big, very expensive and low(er) lumi

- Gamma-gamma Higgs Factories is a viable option from AF side [with where electron beams are used for photons scattering]. Is there a physics interest or a collaboration who is willing to do these studies?

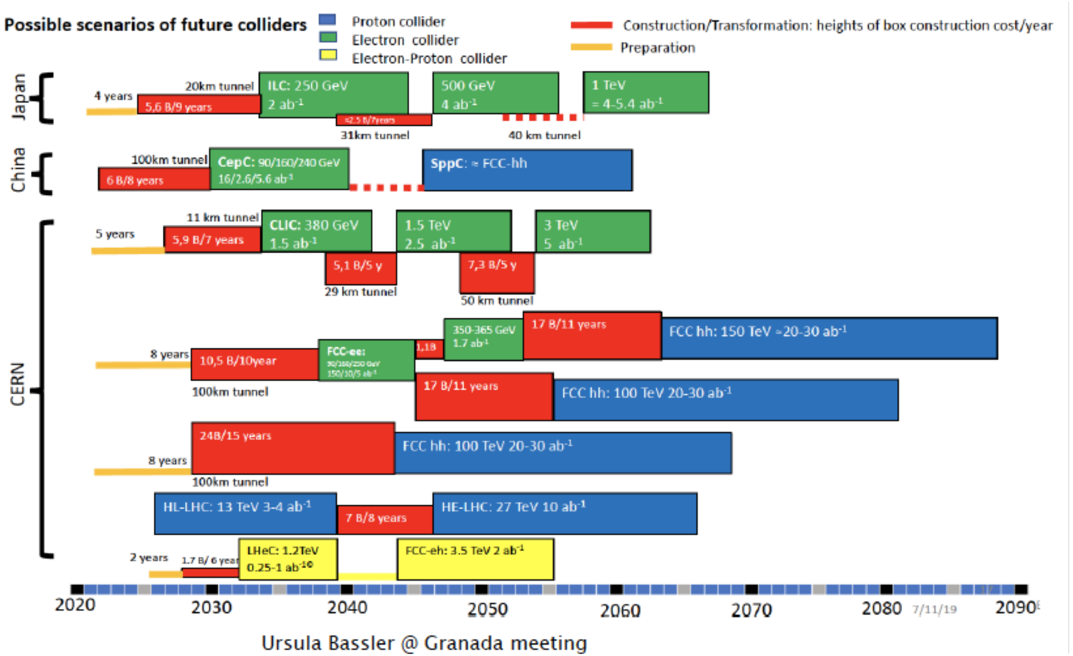
- LHeC: another way to get to Higgs and upto ~1 TeV

Dream ON!

From our EF02 colleagues (Meade,Ojalvo):



Future Collider Scenarios & Timelines from ESPP
Update needed to this chart during Snowmass 2021



- Will add **EIC** and **Muon Collider** to this chart.
- Will consider **new proposals** that may come up during Snowmass 2021.
  - e.g. initiatives for gamma-gamma and plasma colliders etc.

Some “Open Questions” from AF for EF to consider

- AF is soliciting LOIs for all collider options and would like interested colleagues from EF to join the LOIs and provide input from the physics case
  - [US HEP colleagues are encouraged to contact the AF-EF liaisons: Dmitri Denisov and Meenakshi Narain]
- How can U.S. participate in various collider options
  - What would be our focus?
  - While some future collider options have definite stakeholders (and advanced planning/studies) (e+e-/hh), a few collider options in early stages of studies (e.g muon collider)
- How do we play parts in global collaborations – e.g. ILC, CLIC, FCC, Muon Collider Collaborations etc?

e+e- colliders

- During the next year, our focus would be to compare the physics sensitivities of circular vs linear e+e- colliders and their complementarity
  - While an e+e- collider is a preferred choice as the next machine after the HL-LHC, the resources and the global environment will decide
    - Can we afford both a circular and a linear collider ?
    - If we have to make a choice, then the decision will be driven by few main issues
      - Technical feasibility/maturity
      - Cost and timescale
      - And the PHYSICS CASE

- One of the main outcomes of the Energy Frontier studies has to be a detailed comparison of the physics case for the circular vs linear e+e- colliders!
  - There are many studies available already in CDRs for the various proposals
  - There are "open questions and new ideas" which are being proposed to be studied by EF
    - ILC: Study questions for Snowmass 2021
    - FCC-ee: Link to case studies

  - For circular colliders: direct Higgs production, e+e–→H, at the Higgs mass of 125 GeV, is being investigated with the help of a 'monochromatization' scheme.
  - For linear colliders: beam polarizations extend the physics program considerably.

Example Discussion: e+e- linear vs Circular?

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

hristophe Grojean   Future Measurements   9   Inst. Pascal, Dec. 4, 2019

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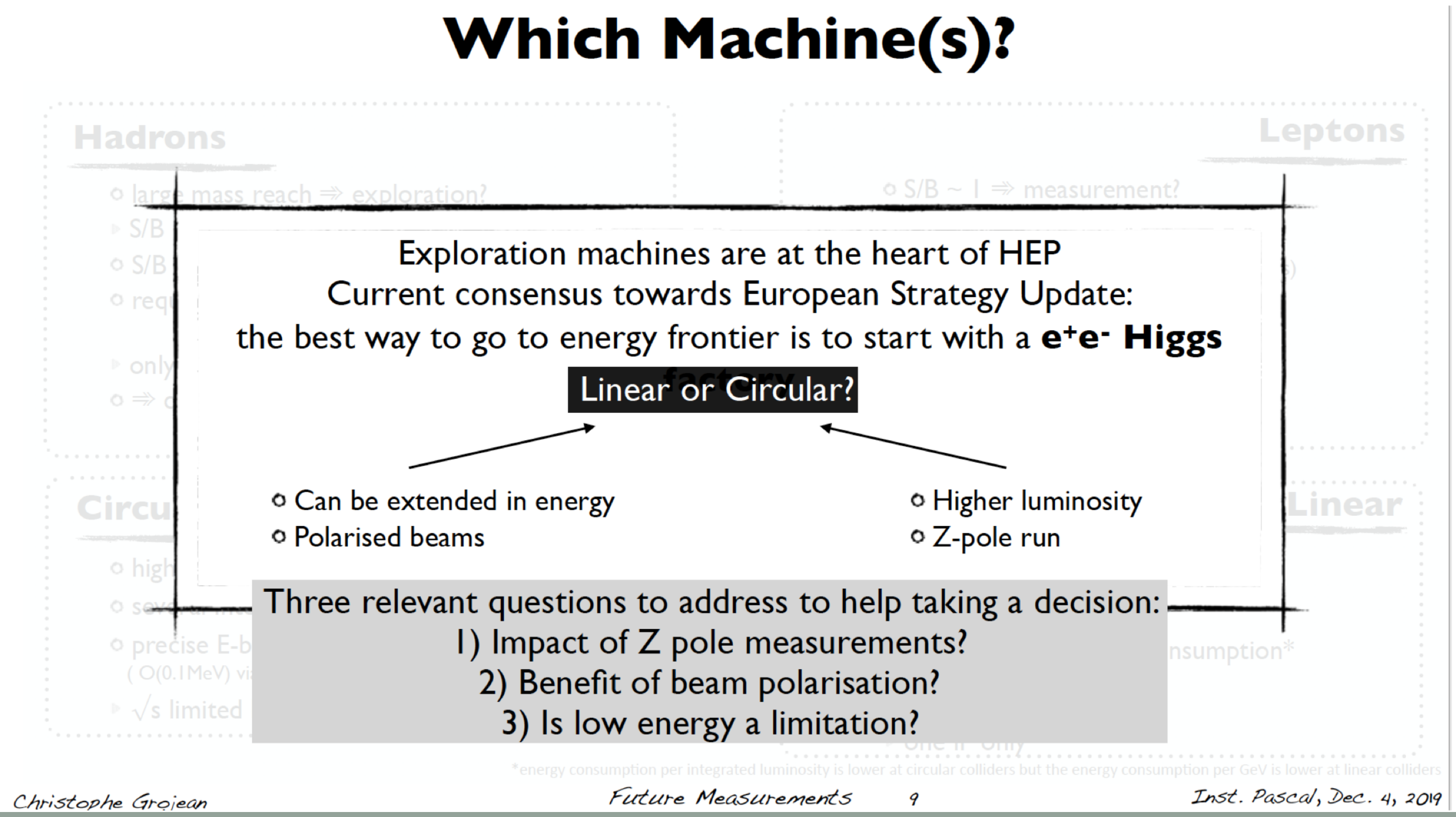


Example Discussion: e+e- linear vs Circular?

Which Machine(s)?

Develop these questions/discussion points during Snowmass2021

Exploration machines are at the heart of HEP
Current consensus towards European Strategy Update:
the best way to go to energy frontier is to start with a **e^+e^- Higgs factory**

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

Three relevant questions to address to help taking a decision:
1) Impact of Z pole measurements?
2) Benefit of beam polarisation?
3) Is low energy a limitation?

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Instrumentation

- Understand the impact of detector designs on physics
  - Conversely comment on the improvement of physics sensitivity as function of a detector parameters

  - The detectors must maintain excellent precision and efficiency for all basic signatures
  - This performance has to be maintain over an immense range of momentum and angle because the detectors must excel at measuring both the relatively low energy decay products of the Higgs boson and the highest energy particles ever produced at an accelerator
  - For example: the 100 TeV pp collider will produce particles with momenta ranging between a few GeV and 20 TeV over $0<|\eta|<6$.
    - These momentum and angular ranges are ten times and twice those achieved at the LHC!

- The proposed collision energies and data rates of the next generation of Energy Frontier colliders impose unprecedented requirements on detector technology.

- A few examples motivated by Higgs Physics at future colliders, which were considered for the DOE Basic Research Needs exercise for future instrumentation
  - Low-mass, high-granularity, radiation-hard, tracking detectors with picosecond timing
  - High-granularity, radiation hard, imaging calorimeters with picosecond timing
  - Integrated high-bandwidth, low-latency, ML-ready trigger and readout

An Example: Requirements for detectors from Higgs Physics

- Technical requirements mostly from existing detector proposals.
- Technical requirements drive technology development
- We should develop further the technical requirements from Physics assessments
  - Is the physics sensitivity limited by a given detector parameter? It would be helpful to assess this.
  - Work with Instrumentation Frontier to understand the constraints and future technology directions which may improve on the detector performance parameters.

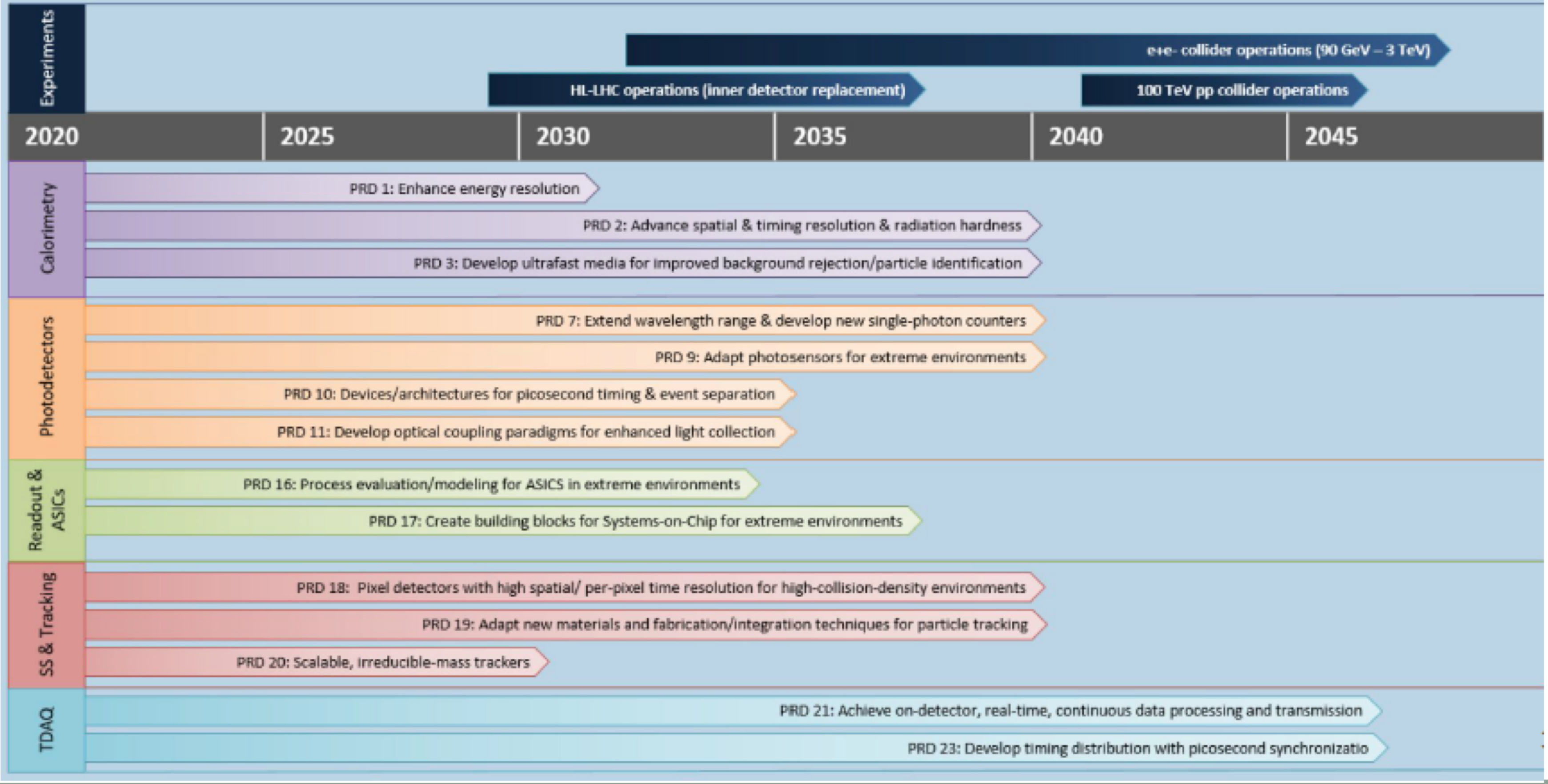
Science	Measurement	Technical Requirement	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu m$ TR 1.1.3: Granularity : $25 \times 50\ \mu m^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ n_{eq}/cm^2$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5 \times 0.5\ cm^2$, hadronic cells of $1 \times 1\ cm^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and $3 \times 10^{16}\ (5 \times 10^{18})\ n_{eq}/cm^2$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ n_{eq}/cm^2$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

Table 2: Technical Requirements [27, 28] to enable the physics program for Higgs and the Energy Frontier and map to Priority Research Directions.

from DOE Instrumentation BRN: [link to talk at HEPAP]

Timeline: Higgs → Technologies to Discovery

from DOE Instrumentation BRN: [link to talk at HEPAP]



Computation

- The Computational Frontier will assess the software and computing needs of the High Energy Physics community emphasizing common needs and common solutions across the frontiers.
- Several topical groups with interests from Energy Frontier:
  - CompF1: Experimental Algorithm Parallelization
    - Parallelization of Detector reconstruction algorithms, physics object reconstruction/calibration algorithms
  - CompF2: Theoretical Calculations and Simulation
    - Describe theoretical calculations, detector simulations, accelerator modelings, event generators that are or will be used by the stakeholders...
  - CompF3: Machine Learning
    - Describe the machine learning training and inference needs of the stakeholders
  - CompF7: Reinterpretation and long-term preservation of data and code
  - +more
- Need to develop engagement and mechanisms for providing input from EF.

Summary

- Develop Physics Focus questions and benchmarks
- Start thinking about technical baselines
    - accelerators
    - instrumentation
    - computation
- Snowmass is a time to for the community to innovate and set new directions without barriers and constraints set by our collaborations.

Let’s collectively **DREAM BIG!**

backup

Identify Focus Questions and Ideas (from May workshop)

- Ideas for investigations that already emerged **in TG Kick-off Meetings**!
- What is the scale of New Physics that can be probed with precision measurement?
- Higgs “inverse problem”: what can we tell about BSM from Higgs couplings?
- How can theoretical precision match experimental precision? When is this necessary?
- Develop model-agnostic BSM physics using Machine Learning techniques.
- What is the value of new colliders? What is the motivation to do physics there?
- Explore new detectors and capabilities that enable new signatures.
- ...

Energy Frontier: exploring the TeV scale

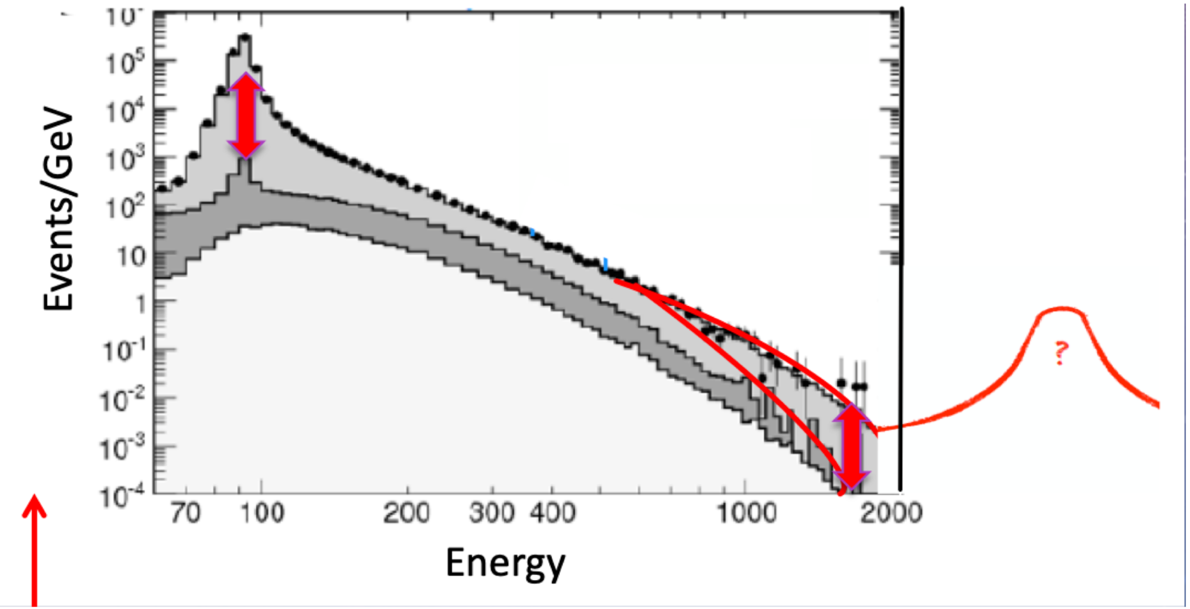
Snowmass 2013: in the wake of an amazing discovery

- Right after **LHC Run 1** and the **Higgs discovery**.
- Opening of a **new era of SM precision physics** and **BSM explorations**.

Moving forward, we need to consider:

- More luminosity → precision measurements
- Higher energy → extend reach of direct searches
- Improved theory predictions → affect both

Energy Frontier: exploring the TeV scale



(from F. Riva)

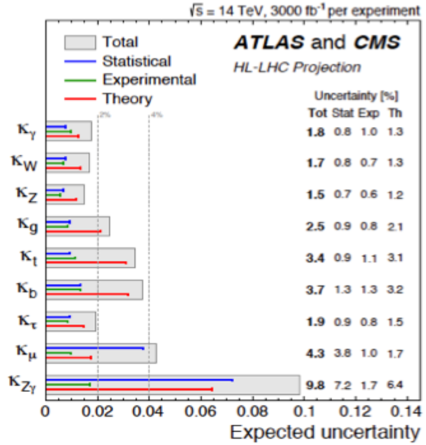
- Precision: indirect evidence of deviations at low and high energy.
- Energy: direct access to new resonances.

Energy Frontier: exploring the TeV scale

Stress-testing the Higgs sector

κ=(measured coupling)/(SM coupling)

	CMS	ATLAS
k_Z	$.99^{+.11}_{-.12}$	$1.10^{+.08}_{-.08}$
k_W	$1.10^{+.12}_{-.17}$	$1.05^{+.08}_{-.08}$
k_t	$1.11^{+.12}_{-.10}$	$1.02^{+.11}_{-.10}$
k_b	$-1.10^{+.33}_{-.23}$	$1.06^{+.19}_{--.18}$
k_τ	$1.01^{+.16}_{-.20}$	$1.07^{+.15}_{-.15}$
k_μ	$.79^{+.58}_{-.79}$	<1.51 at 95% cl



$\Delta\kappa \sim v^2/\Lambda^2 \quad \rightarrow$ sensitive to scale of NP

Higher precision probes higher Λ

% uncertainties with 2 ab^{-1}

	ILC250	ILC500
κ_γ	1.1	1.0
κ_W	1.8	0.4
κ_Z	.38	0.3
κ_g	2.2	0.97
κ_b	1.8	0.60
κ_τ	1.9	0.80

CLIC, % uncertainties

	350 GeV, 1 ab^{-1}	3 TeV, 5 ab^{-1}
κ_γ	-	2.3
κ_W	0.8	0.1
κ_Z	0.4	0.2
κ_g	2.1	0.9
κ_b	1.3	0.2
κ_τ	2.7	0.9

Energy Frontier: exploring the TeV scale

Difficult measurement: Higgs self-coupling ↔ EWSB

Collider	Accuracy on κ_λ	Running Years
HL-LHC	50%	12
HE-LHC	10-20%	20
ILC(500)	27%	21
CLIC(1500)	36%	15
CLIC(3000)	+11%, -7%	23
FCC(hh)	5%	13

Double vs single H production?

Indirect measurement?

Other options?

Deviations can be more subtle: not just a rescaling → explore effective interactions

Is that it? Are there more scalars? → direct searches

We still know very little, but we have very powerful constraints to guide us.